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PHASED-ARRAY ELECTRO-OPTIC STEERING OF LARGE APERTURE LASER BEAMS USING FERROELECTRICS

David A. Scrymgeour, L. Tian, Venkatraman Gopalan, Daren Chauvin, and Kenneth L. Schepler

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/s/
Kenneth L. Schepler
Principal Scientist
EOCM Technology Branch

/s/
William R. Taylor, Acting Chief
EOCM Technology Branch
EO Sensors Technology Division

/s/
ROBERT D. GAUDETTE, Colonel, USAF
Chief, EO Sensors Technology Division
Sensors Directorate

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David A. Scrymgeour, L. Tian, and Venkatraman Gopalan (Pennsylvania State University)
Daren Chauvin (AFIT)
Kenneth L. Schepler (AFRL/SNJW)

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Pennsylvania State University
Department of Materials Science and Engineering and Materials Research Institute
University Park, PA 16802

Air Force Institute of Technology (AFIT)
WPAFB, OH 45433

Electro-Optical Countermeasures Technology Branch (AFRL/SNJW)
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We present a device concept for scanning large (> 1 cm) laser beams using a domain micro-engineered ferroelectric device. In our design, the large input beam is divided into smaller beamlets, which are then individually deflected through an angle, and then recombined in the far field to reconstruct the large beam. As a demonstration of concept, a 5-state cascaded rectangular domain micropatterned scanner device with 11 beamlet channels was fabricated in LiTaO3 and was demonstrated to deflect a 1.064-micron infrared laser beam by a total of 10.3 deg at 5.39 kV/mm.

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Phased-array electro-optic steering of large aperture laser beams using ferroelectrics

David A. Scrymgeour, L. Tian, and Venkatraman Gopalan[a)]
Department of Materials Science and Engineering and Materials Research Institute, Pennsylvania State University, University Park, Pennsylvania 16802

Daren Chauvin
Air Force Institute of Technology, Wright–Patterson Air Force Base, Ohio 45433

Kenneth L. Schepler
Air Force Research Laboratory, Wright–Patterson Air Force Base, Ohio 45433

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We present a device concept for scanning large (>1 cm) laser beams using a domain microengineered ferroelectric device. In our design, the large input beam is divided into smaller beamlets, which are then individually deflected through an angle, and then recombined in the far-field to reconstruct the large beam. As a demonstration of this concept, a five-stage cascaded rectangular domain micropatterned scanner device with 13 beamlet channels was fabricated in $LiTaO_3$ and was demonstrated to deflect a 1.064 μm infrared laser beam by a total of 10.3° at 5.39 kV/mm. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1935033]

Electro-optic prism deflectors based on domain inverted ferroelectric crystals have been shown to control the angular position of a laser beam in one dimension with high precision and speed.[1–5] These devices have several advantages over mechanical gimbals and other systems including compact device size, high operating speeds (intrinsic response speeds of >10 GHz),[6] and noninertial deflection.

These devices, however, have strict requirements on the beam size—both in the vertical (thickness) direction and in the plane of the device. The crystal thickness limits the aperture—thicker crystals increase the aperture but also increase the driving voltages. In the plane of the device, the deflection angle is inversely related to the width of the domain prisms.[7] This leads to a tradeoff between aperture size and deflection angles and limits the device apertures to 50–500 μm for achieving angles of 1°–5°. While such small beam sizes are acceptable for applications requiring smaller spot sizes and medium laser powers (such as optical communications, optical data storage, and analog-to-digital conversion) deflecting larger or higher power laser beams is a challenge for this technology.

The proposed device concept for steering wide aperture beams in the device plane is to split the beam into many smaller beamlets which are then scanned separately by an array of individual prism scanners as shown in Fig. 1. Each individual beamlet is deflected separately, and all the deflected beamlets are then recombined to form a single-large beam in the far field. The path lengths of all of the beamlets through the device are designed to be exactly equal, resulting in equal relative phase shifts upon deflection. Any small differences in phase can be compensated by using an electro-optic phase shifter for each beamlet. This approach is similar to phased array scanning where the beam is separated and delayed in the individual channels so that the resultant beam has a shifted phase front.[8] Each individual scanner channel can be composed of any of the different scanner designs discussed in the literature,[1,7,9] the only requirement being that each beamlet channel must avoid overlapping any other channel.

The principle of electro-optic scanning using ferroelectric domain prisms[10] is as follows: In $LiNbO_3$ and $LiTaO_3$ ferroelectric crystals, two oppositely oriented directions of the spontaneous polarization, $\pm P_s$, are along the optical c (or 3 or e) crystallographic axis. Under a uniform electric field, E_3, applied across the crystal, an electric-field tunable index difference, $\Delta n_e = n_e^3 r_{33} E_3$, between the two domain states is created, where n_e is the extraordinary index and r_{33} is the appropriate electro-optic coefficient. If domains are in the shape of prisms (see Fig. 1), the index change at every domain will deflect the light at an angle that depends on the applied electric field. The total output angle of a device composed of a series of prisms is given by

$$\theta_{\text{int}} = \frac{\Delta n_e}{n_e} \frac{NL}{W}, \tag{1}$$

where N is the number of prisms, L is the length of each triangle device, and W is the width of each triangle.[9]

A five-stage cascaded rectangular domain micropatterned scanner device with 13 beamlet channels was de-

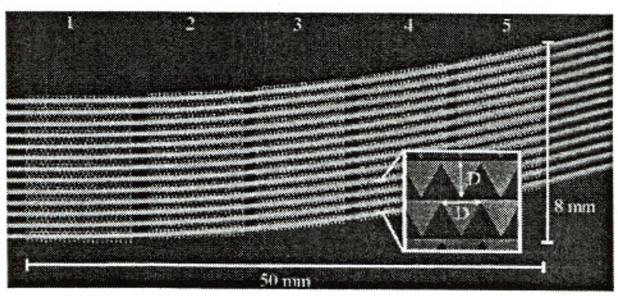

FIG. 1. BPM simulation of a 5-stage, 13-beamlet scanner showing full deflection at 5 kV/mm. The polarization direction of the crystal is perpendicular to the page, with the area enclosed by the triangles opposite in spontaneous polarization (P_s) to the rest of the device. The peak deflection is 10.13° in one direction. The inset is the photolithographic mask fabricated for this device that shows two adjacent scanner channels.

[a)]Electronic mail: vgopalan@psu.edu

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TABLE I. Specification of beamlet scanner.

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Total
Field (kV/mm)	5	5	5	5	5	5
Width, D(mm)	0.444	0.410	0.383	0.362	0.348	8.31
Stage length, L_s (mm)	11.16	10.21	9.45	8.85	8.41	50
Internal deflection (°)	0.96	0.95	0.94	0.93	0.92	4.70
External deflection (°)	2.06	2.04	2.02	2.00	1.98	10.10

signed and fabricated to deflect a 1.064 μm infrared laser beam by a total of $\sim 10°$. The incident beam that was steered in this work was 6.5 mm wide in the crystal plane (though any width beam can be steered in general with this approach). This beam was divided into 13 separate beamlets by a microlens array with 0.5 mm spacing of cylindrical lenses of ~ 50 mm focal length.

Shown in Fig. 1 is a beam propagation method (BPM) simulation[11,12] of the designed device with 5 kV/mm applied to each scanner element with the index of refraction, $n_e = 2.1403$, and $r_{33} = 29.14$ pm/V for light at 1.064 μm taken from tabulated data.[13] Specification of each of the individual scanner stages is given in Table I. Notice that the width of each scanner decreases slightly to accommodate the width of the focused beam in each scanner channel. Each channel is composed of equilateral triangles with height and width equal to the width of the channel, D.

The beamlets were focused into a single electro-optical device and were steered using an applied voltage. This cascaded scanner required a synchronized bias supply for continuous steering operation of the laser beam, i.e., each successive scanner stage must be ramped from 0 V bias to peak bias only after the previous stage is at full bias. A five-stage compact programmable voltage driver was designed and fabricated in a previous study and detailed in the literature, but was unavailable for this study.[14] However, the device was tested with the following configurations: Voltage applied to Stage 1 only, Stages 1+2, Stages 1+2+3, Stages 1+2+3+4, and Stages 1+2+3+4+5. The maximum deflection for each stage and for the total device were measured and compared with the theory.

Without any applied voltage, the beamlet formation process by the beamlet lens array was first analyzed as a function of distance from the output end of the beam steering device. It was found that the microlens array, which divided the beam into beamlets, introduced a complex phase front structure to the beam, but distinct beamlet formation was observed after a distance of ~ 275 mm from the output of the device. Far-field images of the beam were taken by imaging the focal point of a lens ($f = 7.5$ cm) placed at a distance of ~ 30 cm from the microlens array. The 13 beamlets emerging from the beamlet microlens array [Fig. 2(c)] merge into five beamlets in the far field without a device [Fig. 2(a)] or with a device [Fig. 2(b)]. This arises mainly due to the introduction of phase distortions by the beamlet microlens array itself (without the device), as was observed experimentally and confirmed by BPM simulations. The introduction of *active* electro-optic phase control for each beamlet can be implemented to compensate for these phase effects and obtain a single beam in the far field. The scanning of the beam for various bias fields is shown in Fig. 2(c) taken with a Cohu Model ER-5001 camera in a plane at a fixed distance from the exit face of the device.

The steering was tested in a continuous manner for the first stage and is shown in Fig. 3(a). The measured deflection angle versus voltage for Stage 1 agrees well with theory. Figure 3(b) shows a plot of the deflection angle as a function of the number of activated stages running at full bias voltage. The peak deflection was 10.3° at 5.39 kV/mm. The experiments were performed at 5.39 kV/mm, which gives a slight increase of 4.7% in the observed deflection angle over the value when operated at 5 kV/mm. This increase in deflection for fields above the designed value of 5 kV/mm is due to the fact that the scanner channel widths were designed and fabricated to be 60% larger than the focused beam waist as

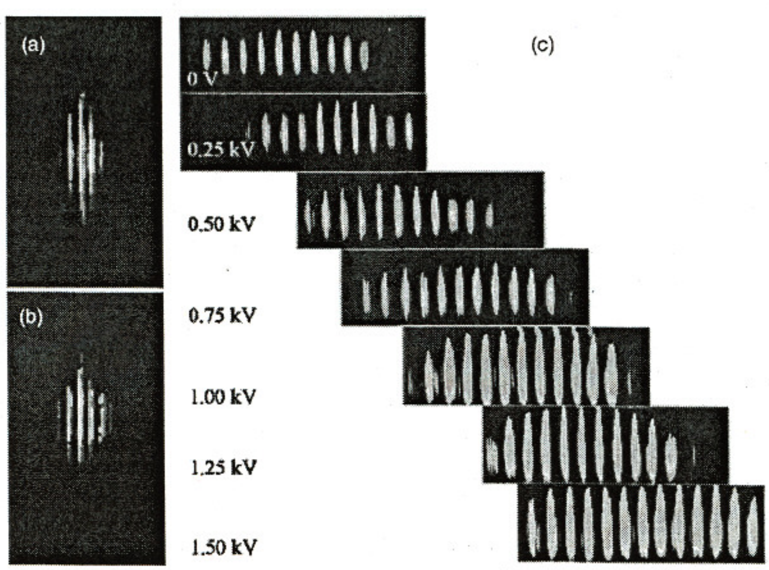

FIG. 2. (a) Far-field images taken of the complex beam pattern introduced by the microlens array as imaged at the focal point of a lens. (b) Shows the far-field beam image with the addition of the device. Both images (a) and (b) are attenuated equally and are 5.4×7.5 mm. Shown in (c) is beamlet steering for various applied voltages. The horizontal panel size is 8.25 mm $\times$ 1.87 mm in (c). The last panel in (c) is taken with camera saturation so that all 13 beamlets can be seen.

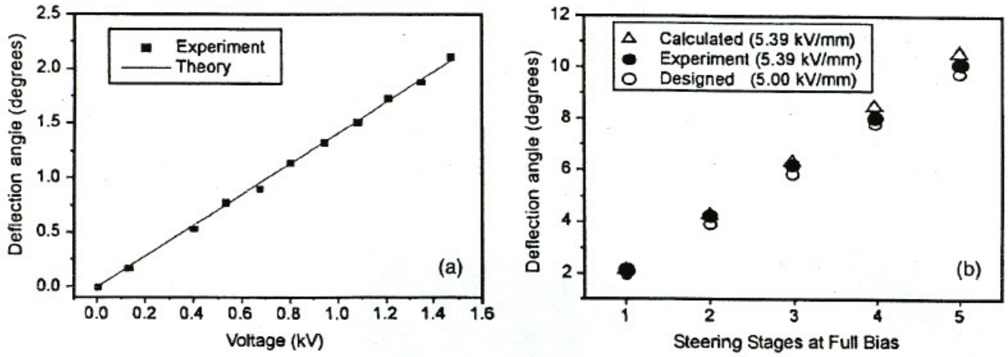

FIG. 3. (a) Deflection angle vs applied voltage across only Stage 1 of the beamlet device. (b) Deflection angle vs the number of steering stages activated in the beamlet device.

calculated from simple Gaussian optics using the specified focal length of the cylindrical lens array. This allows for the application of slightly higher fields than the design specified field. However, this deflection angle is ~4% smaller than the expected calculated value for a field of 5.39 kV/mm. We believe this is due to the higher operating field of 5.39 kV/mm deflecting the beamlets out of the steering portion of the device. Beyond an estimated field of 5.27 kV/mm, no additional deflection can be obtained, and that is the deflection we observe experimentally.

The input and output faces of the beam steering device were not antireflection coated for 1.064 μm wavelength and this resulted in 13.2% loss at each face. With these reflection losses taken into account, the total insertion losses at zero bias were measured to be less than 5%. Ferroelectric domains in congruent $LiTaO_3$ are known to scatter some light, and crystal annealing at 300–400 °C for 12–24 h eliminates such losses.[5] The power loss while scanning was approximately 15% for the full 10.3° of scanning at 5.39 kV/mm. The output face of the crystal was polished inadvertently at an angle of 1.82° relative to the fabricated channels, which resulted in an overall incident angle (to surface normal of the output face) inside the crystal of 6.58° at maximum deflection. Using Fresnel reflection equations for transverse electric polarization, we estimate that the difference in reflectance R between zero deflection and maximum deflection will be ~0.84%, which does not explain the observed power loss on steering. We observed experimentally that the increased loss arose because some fraction of light (~15% power) did not steer fully, and formed a background streak. This is not expected from the device design, if the initial beamlets are fully contained within the channels. One probable reason for the loss is that the phase front and intensity profile of the light beam within 100–150 mm of the beamlet array (near field) are quite complex, [see Fig. 2(a)] and some fraction of light may not be properly traversing through the steering channels.

The convergence of the individual beamlets to form a coherent beam of larger diameter in the far field for arrays of polished prism deflectors and phased optical antennas has been shown previously.[15,16] The exact pattern in the far field is shown to be a function of the beamlet number, spacing, and channel width. The phases of the beamlets converging to an angle θ (in the far field) from two adjacent channels separated by D are normally shifted by the amount $kD\theta$ where k is the wave number. This gives rise to an interference pattern and a modulation of the intensity. However, the component waves can be brought back into phase by integrating small phase shifting electro-optic patches prior to each steering channel. These pads were not included in the current design, but future work will incorporate these.

In summary, we have demonstrated 10.3° of beam steering of 1.064 μm laser light using a beamlet approach. A large 5.5 mm incident beam was split into 13 beamlets, 0.5 mm apart, and all were steered synchronously at 5.39 kV/mm. There is no limit to the number of beamlets, and hence no limits on the incident beam size in the crystal plane in using this design approach. Demonstration of this beamlet scanner is a critical step towards realizing large aperture, large angle beam steering. Further device design improvement can potentially increase these steering angles to 30°–40°. Stacking several such scanners devices in the thickness direction will allow large aperture beams in the thickness direction as well.

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[1]D. A. Scrymgeour, A. Sharan, V. Gopalan, K. T. Gahagan, J. L. Casson, R. Sander, J. M. Robinson, F. Muhammad, P. Chandramani, and F. Kiamilev, Appl. Phys. Lett. 81, 3140 (2002).
[2]J. Zhai, S. Schroeck, Y. Huang, W. Messner, D. D. Stancil, and T. E. Schlesinger, Proc. SPIE 3787, 194 (1999).
[3]J. C. Fang, M. J. Kawas, J. Zou, V. Gopalan, T. E. Schlesinger, and D. D. Stancil, IEEE Photonics Technol. Lett. 11, 66 (1999).
[4]Q. Chen, Y. Chiu, D. N. Lambeth, T. E. Schlesinger, and D. D. Stancil, J. Lightwave Technol. 12, 1401 (1994).
[5]M. Yamada, M. Saitoh, and H. Ooki, Appl. Phys. Lett. 69, 3659 (1996).
[6]J. Noda, N. Uchida, and T. Saku, Appl. Phys. Lett. 25, 131 (1974).
[7]Y. Chiu, J. Zou, D. D. Stancil, and T. E. Schlesinger, J. Lightwave Technol. 17, 108 (1999).
[8]R. A. Meyer, Appl. Opt. 11, 613 (1972).
[9]James F. Lotspeich, IEEE Spectrum 45 (1968).
[10]J. Li, H. C. Cheng, M. J. Kawas, D. N. Lambeth, T. E. Schlesinger, and D. D. Stancil, IEEE Photonics Technol. Lett. 8, 1486 (1996).
[11]M. D. Feit and J. A. Fleck, Jr., Appl. Opt. 17, 3990 (1978).
[12]J. A. Fleck, Jr., J. R. Morris, and M. D. Feit, Appl. Phys. 14, 99 (1977).
[13]T. Yamada, *Landolt-Bornstein Numerical Data and Functional Relationships in Science and Technology*, (1981), p. 149.
[14]F. Muhammad, P. Chandramani, J. Ekman, F. Kiamilev, D. A. Scrymgeour, V. Gopalan, E. Moore, and M. Weiler, IEEE Photonics Technol. Lett. 14, 1605 (2002).
[15]Y. Ninomiya, Electron. Commun. Jpn. 56, 108 (1973).
[16]J. F. Revelli, Appl. Opt. 19, 389 (1980).